

CFD Simulation and Measurement Validation of Air Distribution at the Hunan International Exhibition Center

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Abstract: The Hunan International Exhibition Center (HIEC) is a large space building. A stratified air-conditioning system on the second floor of the building has been adopted. Due to some problems with the air supply jet diffuser, CFD simulations were carried out to predict air distribution. Meanwhile, field measurement results were used to validate the CFD simulation results. A good agreement of simulated and test results was obtained. Based on simulation results, some analyses and suggestions are put forward to improve air distribution.

Key words: Large space building; Stratified air-condition; Air distribution; CFD

1. FOREWORD

The design method of air conditioning system in large space building is different from general space. Because of the greater height and larger floor area, it brings some problems for air conditioning design, especially for air distribution design. Using the stratified hot jets diffuser in sidewall, the hot current seldom reaches the working area for the buoyancy lift action of the hot current in winter. So it can not satisfy the demands of personnel thermal comfort and the irrational air distribution makes a great deal waste of energy etc^[1-2]. In recent years, more and more stratified air-conditioning systems are adopted in the large space buildings (such as exhibition hall, industrial workshop and supermarket). However, there are not mature theories and experiment conclusions for air distribution design in large space building^[3-4]. The study methods of air distribution include experiment method, simplified model, and the most important method is the combination

method between airflow numerical analyses and model experiment. But the latter costs more time and cost than the former. With the development of computer technology, the computer numerical simulation method has advantages of quick speed, lower cost and detail data and so on. Meanwhile, it can preferably study various possible internal disturbances, boundary conditions and initial conditions, and the simulation results can completely characterize air distribution, so the optimum design scheme of air distribution can easily be obtained. Therefore, numerical simulation not only gains the effect of model experiment, but also saves the cost and time. Among all the simulation tools, CFD technology is applied by the most engineers^[5-7]. To predict of air distribution driving by the stratified air-conditioning jets diffuser in sidewall in the second floor of Hunan International Exhibition Center (HIEC), CFD simulation is carried out in this paper.

2. THE INTRODUCTION AND PROBLEMS IN HIEC

The steel structure is adopted in HIEC, which includes 2 floors. The height of first one is 12.5 meters. The main hall area has about 20,000 square meters. The layout of second floor is concave shown as Fig. 1. The steel structure arch roof is adopted. The highest height reaches about 30 meters. There are some conference rooms around this building, which adopt water-air conditioning system. The stratified air conditioning jets diffuser are used in the second floor of the main exhibition hall, which supply air flows from side to the middle, including double layer jets diffuser form in the concave space and singer layer

jets diffuser form in two side spaces, shown as Fig.2.

This construction is finished several years ago. At the using in winter, the hot current can't reach the occupied region according to field experimental measurements. For this problem, CFD method is conducted to predict air distribution in second floors of HIEC. Based on the numerical simulation results, some suggestions are brought forward to improving the design scheme of air distribution.

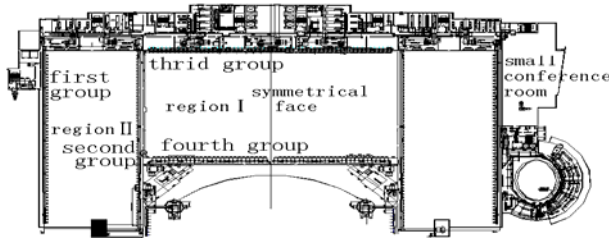


Fig. 1 International exhibition center in second floor plane figure

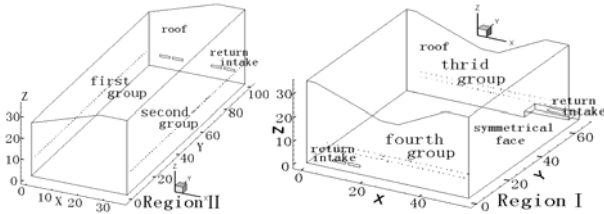


Fig. 2 Building physical models

3. NUMERICAL SIMULATIONS

3.1 Physical model

Second floor of HIEC is nearly symmetric layout, so only half region simulation is enough. The main exhibition hall is divided into region I and II, respectively. The simple physical model and the distribution of jets diffuser are shown in Fig.2. There are 55 jets diffuser in the first group set at 8.5m and 54 jets diffuser in the second group at 10.5m height away from the ground in region II.

In region I, the 58 jets diffuser in third group is arranged at 7.5m or 9.7m height from the floor. The 56 jets diffuser in fourth group is arranged at 8.5m or 10.6m. The TROX DUK $\phi 400$ jet diffuser is regarded as the long project distance form. The jet diffuser angle is 30° down with horizontal direction. Return intakes of region I and region II are 3m and 5m height away from the ground respectively.

3.2 Mathematical model and boundary conditions

The airflow in the exhibition hall is non-isothermal three-dimensional turbulent flow. Boussinesq hypothesis is adopted to describe the buoyancy lift. Commercial software FLUENT6.2 with RNG $k-\varepsilon$ turbulence model is used to simulation the air distribution, the finite volume approach is used to solve discretized equation 1, and SIMPLE algorithm is used to solve velocity equation coupled with pressure equation. N-S transport governing equations are as follows:

$$\frac{\partial(\rho\phi)}{\partial\tau} + \text{div}(\rho U\phi) = \text{div}(\Gamma \text{grad}\phi) + S \quad (1)$$

Where ϕ is variable, include u, v, w, k and ε , S is source item, Γ is diffusion coefficient.

Boussinesq formula is assumed to be momentum equation:

$$(\rho - \rho_0)g \cong -\rho_0\beta(T - T_0)g \quad (2)$$

Where thermal expansion coefficient is

$$\beta = -\frac{1}{\rho} \frac{\partial \rho}{\partial T} \quad (3)$$

Thermal expansion coefficient β is 0.00336, referenced air density is 1.225kg/m^3 , and temperature is 286K in this simulation case.

The boundary condition of jet diffuser is a difficult problem in numerical simulation of air distribution in ventilation air conditioning room [8]. In mathematical aspect, as for CFD nonlinear partial differential equation group, the boundary conditions are important for the influence on the computational accurate solutions. In physical aspect, the airflow of large space is caused by jet diffuser, and the momentum and mass flow of jet diffuser play a critical role on air distribution. Direct description method, including basic model and momentum model, direct describes the boundary condition on the Supply air outlet and is not

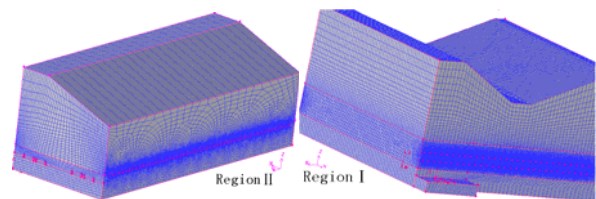


Fig. 3 Grid division of second floor

Table 1 Boundary Conditions of Second Floor of HIEC

Item	dimension	unit	Item	dimension	unit
Single jet supply air volume	2240	m ³ /h	Floor heat load	20	w/m ²
Jet's outflow temperature	34	□	Exterior wall	2.48	w/(m ² *K)
Outside temperature	11	□	Roof	2.85	w/(m ² *K)
Corridor average temperature	14	□	Inner wall	2.59	w/(m ² *K)

restrained by jet outflow's isothermal condition. Therefore, direct description method is a simple model in practical application, and can describe size of jet diffuser directly. But the disadvantage is that the modeling is complicated, and generating mesh is difficult. So the prismatic and hexahedral grids are adopted to partition the total zone. Local refinement at the jet diffuser is accepted. The volume of grids at jet diffuser is reach to the millimeter level. The grids amount of region I is about 2,630,000 and region II is about 1,870,000(fig.3). DUK—V is adjustable jet diffuser, the effective diameter of it is 398mm^[9]. The other concrete parameters are shown in Table 1.

4. CALCULATION RESULTS AND ANALYSIS

4.1 Velocity, temperature nephogram and vector distribution of sections in region I

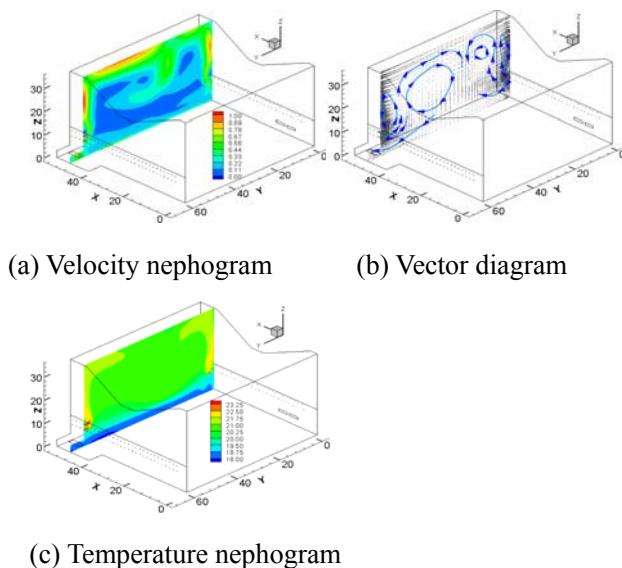
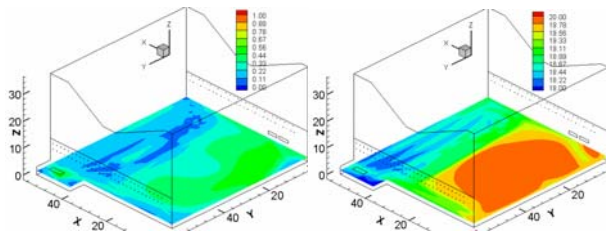


Fig. 4 Velocity, temperature nephogram, vector diagram (X=48.5m)

Fig.4 is a section of X=48.5m in region I, which cutting by return intake and jet diffuser center. The

jet's outflow velocity drops down rapidly. After hot current leaving the jets diffuser off a short distance, the airflow moves upward with entraining cold air. And exchanges heat with the roof then downward from the middle of space to the return intakes; the velocity distribution is shown Fig.4 (a). The velocity at the bottom of space is about 0.2m/s, there is no existence at the field measurement. This may be caused by additive the personnel thermal load to floor at the simulation, and enhances the convection on the floor. In the whole occupied region, the velocity of airflow is low, and the temperature distribution in total space is uniform. The temperature at the top zone is 2℃ greater than at the bottom zone. The average temperature of the region I is about 19℃, and can not demands the thermal comfort. It is show that, the design of air distribution in region I is unreasonable.

The velocity and temperature nephogram at Z=1.5m is a cross section in the occupied zone (Fig.5). The velocity at the exhibition hall center is about 0.1m/s and velocity of close to the wall is about 0.4m/s, shown as Fig.5 (a). the mainly reason is that without regard to air leakage, the return air rate is 100 %, the hot current entrain the periphery air under the buoyancy lift action, reach to the top roof and convect with cold wall, then return to the bottom along the cold wall. At the same time, there are two return intakes vicinity of cold wall, so the local velocity becomes larger. As Fig.5 (b), the air temperature is comparatively higher where the velocity is larger. Due to air leakage of aloft slit, the upstream directly exhaust to outside from the slits in practical situation. Thus the local region of larger velocity is inexistence, so the hot current didn't reaches to occupied region, and didn't meet the demand of ideal condition.

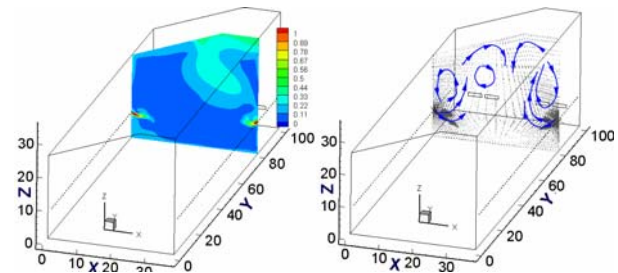


(a) Velocity nephogram (b) Temperature nephogram
Fig. 5 Velocity and temperature nephogram
 (Z=1.5)

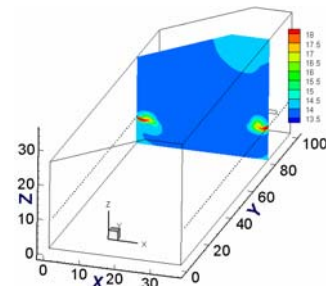
4.2 Velocity, temperature nephogram and vector distribution of sections in region II

At $Y=78.6\text{m}$ in region II, shown as Fig.6. The jets diffuser slope down to 30° , under the action of inertial force, the jets deliver air along the jet's axial direction down off. After it arrives to certain horizontal distance, the tendency of the hot current drops down become upwards action with the entrainment air increasing. Jet's main flows up like a bow. because the setting height of left and right jets are 8.5m and 10.5m apart from the ground, respectively. The downward tendency of airflow from the left jets diffuser is obvious, under compression of the airflow from the right jets diffuser. On the other hand, the upward tendency of airflow from the right jets diffuser is obvious too, under the extrusion of left jets diffuser. As Fig.6(c), a little circulated airflow is formed at the above of right jets diffuser, this is because entrainment air moves upwards under the buoyancy force and reaches to the top of jets diffuser, and sends outwards under the entrainment air of jets flow, thereby forms a very obvious vortex. In the middle part of space and occupied region, the velocity is nil. It is indicate that the hot current didn't reach the ideal air supply state. In the upper zone, the airflow velocity are relatively larger, it maybe caused by greater heat exchange between hot current and cold roof, and enhance of convection effect. The hot current from the jets diffuser mixes rapidly with the surrounding air, and it causes the velocity of axial center falling down quickly. At the same time, the temperature around the jets diffuser is relatively higher than the entire cross-section. This is because jets diffuser is under the vortex action. The impact of airflow from jets diffuser on the occupied region is

not remarkable as does the middle of larger space. Due to the heat exchange between hot current and the cold walls or roof is big, it causes the average temperature of indoor air is low.



(a) Velocity nephogram (b) Vector diagram

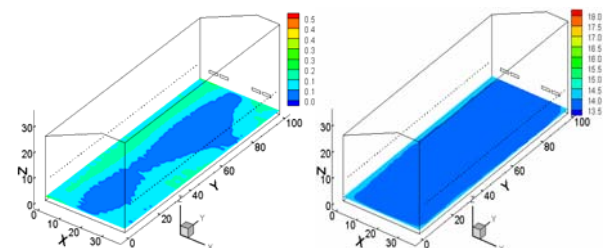


(c) Temperature nephogram

Fig. 6 Section velocity, temperature nephogram and vector diagram of region II ($Y=78.6$)

At $Z=1.5\text{m}$ in region II. As Fig.7 Air velocity nearly nil in the cross-section and average temperature is about 14°C . Hot current from the jets diffuser didn't impact on the occupied region. In field measurement, airflow velocity is very low at the lower zone and has a good agreement with the simulation result.

4.3 Simulations and analyses results of region I and region II

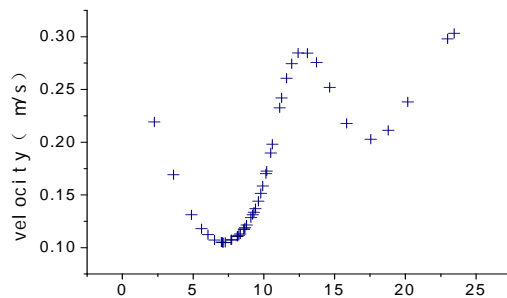


(a) Velocity nephogram (b) Temperature nephogram
Fig. 7 Velocity, temperature nephogram ($Z=1.5$)

4.3.1 Velocity distribution along vertical height in region I

Velocity distribution along vertical height reveal the characteristics of jets diffuser, can indicate the mutual relations between the installation location of jets diffuser and air distribution in large spaces

building. Fig.8 is the vertical velocity distribution through geometric center (a) and velocity distribution diagram of jets diffuser in fully developed (b).



(a) The velocity distribution along vertical line



(b) Velocity distribution of jet diffuser (c) The line locations in region I

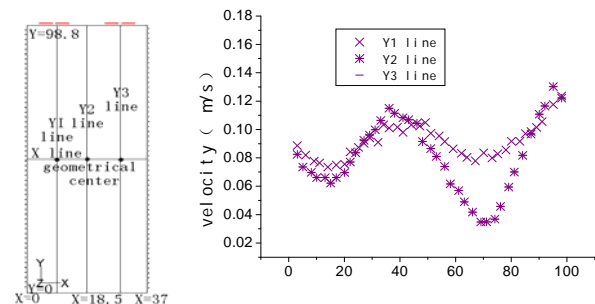
Fig. 8 Compare velocity distribution at vertical height with the jet diffuser in region I

Fig.8 (a) shows that the vertical velocity distribution. Below the vertical height 2.5m; the velocity is about 0.15m/s, vertical height from 2.5m to 5m, the velocity reduces from 0.2m/s to 0.1m/s; vertical height from 5m to 13m, the velocity goes up, then vertical height from 13m to 18m, the velocity falls down. Until to 18m, the velocity rises again. This velocity distribution is related with the characteristic of the jet diffuser (Fig.8 (b)). The occupied region is less than 2.5m, and the hot current didn't impact on it. The zone of vertical height from 2.5m to 5m is return flow region of jet diffuser, and the velocity at the lower part of it is relatively larger. There is an interface at about $Z=5m$. The zone above the interface belongs to entrainment region of jet diffuser. Velocity gradually increases and arrives at the mainstream region. The location of largest velocity is about $Z=13m$. From the velocity distribution along vertical direction, the mainstream region rises about 2m than the jet diffuser is isothermal. due to the influence of buoyancy lift by hot current. The ascent of the mainstream region

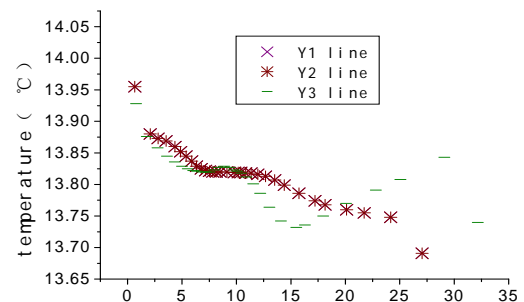
leads to the occupied region below the return flow region and causes no hot current reached it. Fig.8 indicates that jet diffuser have little effect on the occupied region because of the mainstream region rising.

4.3.2 Temperature and velocity distribution in region II

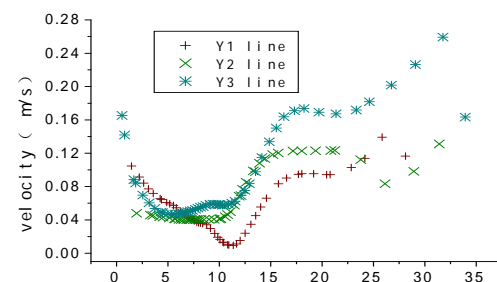
Fig.9 shows the velocity and temperature distribution along different directions at $Z=1m$ in region II. Thus, the air distribution of occupied region can be known well.



(a) The line locations in region II (b) The velocity distribution along Y direction



(c) The temperature distribution in Y direction



(d) The velocity distribution of vertical direction

Fig. 9 Velocity and temperature distribution in different lines in region II

Fig.9 (a) shows velocity distribution along Y direction in region II. The velocity is the range of 0.04m/s and 0.12m/s. the velocity distribution have same trend at three lines, and indicates that the velocity distribution is similar at three zones in a cross section of $Z=1m$. The velocity distribution

indicate that close to two walls is larger and the middle part of space is smaller, this is because of the hot current from jets diffuser uplifts to the upper space, then falls down along the cold wall ($Y=0$). At the same time, There are two return intakes at the wall surface ($Y=98.8$), the velocity will go up at this zone. In entire cross section, the velocity is low, which indicates that the design of air distribution in the HIEC is unreasonable. As Fig.9 (b), the temperature distribution is uniform. And the average temperature is about 14°C . Fig.9 (c) shows the velocity distribution along three vertical lines. The velocity growth trend in three zones is uniform too, which is similar to that of the velocity distribution of region I, and also be consistent with the characteristic of the jets diffuser. The velocity distributions along Y1 and Y2 line are mainly effected by the first group jets diffuser and the second group jets diffuser, respectively. The velocity along Y2 line is slightly greater than that of Y1 and Y3 line. The zone area of return flow is small in the central part of Y2, thus the corresponding back flow velocity is relatively larger. In the top roof of region II, the velocity of Y3 line is larger than of Y1 line, which conforms to abovementioned analysis.

4.3.3 Comparison of region I and region II

Air supply condition of region I and region II are not ideal. According to analyses, the different situations can be found to guide the design of air distribution. Table.2 and Fig.10 are the detailed parameter comparisons of region I with region II.

To a certain degree, vertical temperature gradient distribution determines heat and cooling load, which is determined by air distribution in the large space building. Whether summer or winter, vertical temperature gradient produces air density difference and it can produce stratified temperature in large space building. Fig.10 (a) shows average temperature of vertical cross-sections in two regions. The average temperature in region I is about 20°C .

Table.2 Parameters comparison of the region I with region II

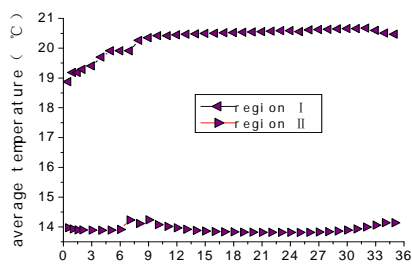
	region I		region II
Numbers of jets and height(m)	29(7.5)	28(8.5)	55(8.5m)
diffuser	29(10.6)	29(9.7)	54(10.5m)
Air supply area (m^2)	3430		3659
Total air supply volume (m^3/h)	257398		221586
Average temperature at height of 1.5m($^{\circ}\text{C}$)	19.2		14.1
Average velocity at height of 1.5m(m/s)	0.21		0.082

Below the Vertical height of 8m, the average temperature increases from 18.5°C to 20.5°C . Upon vertical height of 8m, the average temperature is about 20.5°C . The temperature different along the vertical direction is obvious. In winter, if the stratified temperature is distinct. The energy utilization effectiveness will low, so lower vertical temperature gradient is an important measure for saving energy in winter. The average temperature along vertical direction in region II is more uniformly, the average temperature is about 14°C , and drops down 5°C than region I. This is mainly because of in same areas, the supply air quantity of region I is greater than that of region II, and the wall area of directly contacted with outdoor air are larger in region II, so the region II has relatively larger thermal load, and leads to the average temperature drops down.

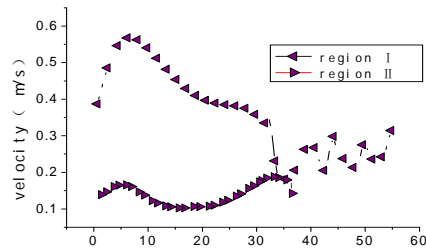
5 CONCLUSIONS

From the above analyses, we can probably know air distribution of the second floor of HIEC. Due to the higher jet mainstream region, the air distribution in second floor is not reasonable and the occupied region is not in return air region (Fig.11). According to the simulation results, some suggestions for improving the air distribution are summarized as follows:

1) Increasing the air supply volume.



(a) The average temperature in vertical direction



(b) Velocity at geometric center along with the X direction

Fig. 10 Compare velocity and temperature distribution in region I with region II

According to the comparison of the region I with region II, if the air supply volume increases, the airflow velocity from jet goes up, then the occupied region can change to locate in the back flow region. As a result, it will satisfy the demand of personnel thermal comfort.

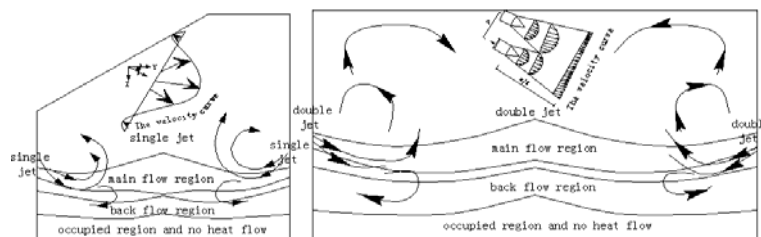
2) Reducing the setting heights of the jets diffuser.

Fig.11 shows that with the influence of buoyancy of hot current in winter, the heights of the mainstream region increases and so does the return flow region, which causes the result that the occupied region is not in return flow region and hot current can not be sent to the occupied region. As the setting height of the jets diffuser decreases, the mainstream region and return flow region heights decrease correspondingly, which brings the occupied region

back to the return flow region. The further study is going to determine the optimal height of the jets diffuser and air volume that meet the demand of thermal comfort in occupied region.

REFERENCES

- [1] Fan Cunyang. Design and Engineering Real Records of the Air-condition in Larger Spaces Building [M]. Beijing: China Architecture & Building Press, 2001.
- [2] Zou Yueqin, Wan Shibai, Peng Rong, etc. Research on computer method for airflow organization of striated air condition [J]. Heating Ventilation Air Conditioning (HV&AC), 1983, 13(2): 1-7.
- [3] Xiao Dong, Gao Jun, Xu Shijie. Numerical Simulation and Discussion on Stratified Airflow Organization by Sidewall Air Supply in Large Space Building [J]. Building Energy& Environment, 2004, 23(2): 64-66.
- [4] Zhao Rongyi, Fan Cunyang, Xue Dianhua, Air Conditioning (The third edition) [M]. Beijing: China Architecture & Building Press.
- [5] Guan Qing, Tang Guangfa. The Numerical Research of Strand Parallel Non-isothermal Restricted Jet [J]. Journal of Aerodynamics.1992, 10(3): 390-395.
- [6] Gong Guangcai, Tang Guangfa, Chen Zaikang. Numerical Simulation of Horizontal-Partition Airflow in Large Space [J]. Journal of Hunan University,1998, 25(4): 71-76.
- [7] Huan Chen ,Li Meiling. Research of Indoor Vertical Temperature Distribution in Large Space Building [J]. HV&AC, 1999,29 (5) : 28-33.
- [8] Zhao Bin, Li Xianting, Yan Qisen. Summary of Tuyere Models in Numerical Simulation of Indoor Airflow [J]. HV&AC, 2000, 30(5).
- [9] TROX. air conditioning technology Concise handbook [M]



(a) Air distribution schematic of region II (b) Air distribution schematic of region I

Fig. 11 Air distribution schematic of second floor of HIEC